Solar Turbines Perspective on Advanced Fuel Cell/Gas Turbine Systems

SUMMARY

Solar Turbines Incorporated (Solar) has a vested interest in the integration of gas turbines and high temperature fuel cells and in particular solid oxide fuel cells (SOFC). Solar has identified a parallel path approach to the technology developments needed for future high efficiency energy conversion products and one of these paths includes fuel cells. The primary approach is to move away from the simple cycle industrial machines of the past and develop as a first step more efficient recuperated engines. Recuperated engines would be followed by more efficient intercooled and recuperated (ICR) engines and finally by a humid air turbine (HAT) cycle system. This latter engine system would be capable of providing efficiencies on the order of 60% with potentially low exhaust emissions.

Because of the many unknowns facing industry in the first two decades of the next century such as possible fossil fuel shortages and severe carbon dioxide emissions regulations Solar adopted an alternative approach in the development of high efficiency machines. The approach is intended to provide overall thermal efficiencies, at the terminals, higher than 60% with emissions lower than any possible with a gas turbine. This alternative path is dominated by the concept of combining the technologies of solid oxide fuel cells with those of recuperated gas turbines.

INTRODUCTION

Integration

There is a synergy between the SOFC and the recuperated gas turbine particularly those with firing temperatures below 1800 F. The two systems together can reach higher efficiencies than either alone.   Recuperated gas turbines using fuel cell systems in the “topping mode” will have lower capital costs, higher power densities and lower losses when compared to other approaches. The topping mode refers to the system configuration in which the fuel cell occupies the position that the gas turbine combustor usually does and replaces it for steady state operation. In essence, the gas turbine uses the fuel cell as both a solid state generator and a combustion system. In practical systems the gas turbine will produce power in parallel with the fuel cell. This approach allows the gas turbine to provide all the necessary power for the ancillary equipment during fuel cell warm-up.

The combined SOFC and gas turbine called at Solar the Tandem Cycle Power System (TCPS) will be cost competitive in terms of the cost of electricity (COE) produced, with all other future energy conversion system. This combination TCPS will have an advantage over most heat engine systems because it will have much lower NOx emissions and much lower carbon dioxide emissions on a per kilowatt basis.

Market

The market niche for the initial product entry will be the dispersed or distributed power market in city and urban areas that suffer severe air pollution. Once established in this market, it is expected that the TCPS will gradually penetrate all of the other power generating market segments. The first entry into the dispersed power market will take place between 2000 and 2002 with units in the 1 to 2-MW size range. These units will probably sell initially for $1400/kW dropping to $1000/kW when series production is underway. Larger units ranging in size from 3 to 10-MW will be introduced as market acceptance for this new power generating system is gained.

Development

The development requirements for the fuel cell elements have been identified and will have to be completed early if the combined SOFC and gas turbine or TCPS is to become a reality. For the fuel cells lowering the cost of manufacturing is critically important. Great strides have been made recently and the manufacturing cost goals of $500/kW are likely to be reached soon. Internal fuel cell sulfur tolerance needs to be developed because it will eliminate 1) the requirement to remove sulfur from fuels, and 2) the concomitant solid waste disposal problems. Careful integration of both the gas turbine heat exchange and fluid distribution systems with the internal fuel cell components will also have to be accomplished to attain the desired high efficiencies.

The recuperated gas turbine portion of the TCPS will also require some development. The two most important requirements involve the development of a start combustor and the creation of an overall TCPS control system. A combustion system (start combustor) in series with the fuel cell will be required to provide a “black-start” capability. To start, the gas turbine portion of the system will be lighted and the engine accelerated to its full power condition. Hot air from the recuperator will then heat the fuel cell to a temperature high enough that when fuel is supplied to the fuel cell “light-off” can occur. After starting the combined system, the start combustor will be turned off and will have to endure the exhaust stream of the fuel cell. This oxidizing stream will pass through the combustor at a temperature between 1550 F and 1800 F. The fuel system for the start combustor will also have to withstand a similar temperature range. Integration of the gas turbine with the fuel cell will require some modifications to the ducts connecting the gas turbine to the recuperator.

Basis for Interest

Solar has recognized the importance of developing very high efficiency energy conversion products. These products are dominated by the combining of solid oxide fuel cells and gas turbines referred to as the Tandem Cycle Unified Power System. The TCPS will require gas- turbine- like products similar to those presently being produced at Solar. It is the promise of significantly increased efficiency and power output of these gas turbine systems, with reduced exhaust emissions, that drives the development of TCPS. Solar also has developed technologies in fuel reformation and in electrical inverters. Both of these technologies will aid in the creation of a practical TCPS.

It is recognized that a practical upper limit in efficiency for the TCPS exists and this is on the order of 78%. Small systems of under 5-MW will have efficiencies between 58 and 63% for the introductory units. Later production units employing optimized internal integration of the fuel reformer and fluid distribution systems will have higher efficiencies. High power systems above 5-MW employing a SOFC reheat step could have efficiencies as high as 75%. TCPS producing 20-MW and above will approach the upper limit of 78%.

MARKET ENTRY

Initial Offering

Solar envisions a market entry TCPS with a power level between 1 and 2-MW and a thermal efficiency of 58%. This device, with its extremely low exhaust emissions, will be targeted at the dispersed power market in urban areas with severe air pollution. At this power level and efficiency the system should enjoy considerable market success if the cost targets are met. This size TCPS will be based on a 310-kW recuperated gas turbine fitted with a direct drive alternator. This system, at the present time, is in a demonstration phase. The modifications needed to combine the SOFC as a topping unit with this engine are considered minimal.

Preferred Configuration

In general recuperated engine systems with low firing temperatures will be the gas turbines of choice to be combined with fuel cells. Simple-cycle machines will require extensive conversion to adapt them to fit with a fuel cell. In particular high pressure large gas turbines are generally not recuperated and thus fall into the category of difficult and costly to modify. Solar intends to produce under the auspices of its Advanced Turbine Systems (ATS) program, a family of recuperated and related engine systems. This family of engines will provide the basis for several TCPSs ranging in size from 800-kW to 20-MW. Thus the fuel cell integration program and ATS are supportive of and synergistic with each other.

PREFERRED-CYCLE TECHNOLOGY

Synergy

The mode that provides the highest level of synergy between the SOFC and the gas turbine is the "topping" approach. In this technique the fuel cell takes the place of the gas turbine combustor (during steady-state operation) and provides hot exhaust gases to the turbine section. In essence the fuel cell acts as a combined combustor and solid-state electrical generator. In a practical system a combustor will be needed for starting purposes. A generator will also be required to load the gas turbine during starting and the output from the generator will provide the power for the controls and ancillary systems. Batteries or power from the electrical grid will be used to provide the initial power to spin the engine to the required light-off speed.

Other Cycles

Other integrated cycles where the fuel cell is used to "bottom" the gas turbine have been considered as have indirect-fired approaches. Solar has some interest in the bottoming cycle which fits a molten carbonate fuel cell (MCFC) into the exhaust section of the gas turbine. This type of integration could utilize any gas turbine system. The whole fuel cell would be integrated into the gas turbine exhaust. The positioning of the fuel cell In the exhaust creates a back-pressure on the gas turbine reducing the power produced significantly. The indirect-fired approach posits the fuel cell In the exhaust of an indirect fired gas turbine. The air and combustion products of the fuel cell are then fed as the air supply to an atmospheric combustor. This combustor heats the air leaving the compressor via a heat exchanger and delivers it to the turbine. The combination of the atmospheric combustor and heat exchanger, replaces the normal internal pressurized combustor. The main problem with the latter system is that the heat exchanger has to operate at a temperature close to 2000 F to achieve high efficiencies. There are, at present, neither materials nor heat exchanger design methodologies capable of producing a heat exchanger that can operate at these temperatures.

Because of the difficulties presented by the bottoming and indirect-fired approaches Solar has opted for the topping cycle.

SYSTEM COSTS

The synergy between the gas turbine and the SOFC is the key to the cost effectiveness of the combined system. Provided SOFC manufacturing costs decrease with increasing production levels, a factory cost of below $500/kW should be achieved. Over time it is anticipated that this cost will decrease (with improved manufacturing techniques) to approximately $400/kW. The life cycle costs of the TCPS, because of the extremely high efficiency, will be much lower than either the gas turbine or fuel cell alone. The advantage that the TCPS has over competing heat engines is that it probably will have extremely low NOx levels which will allow it to be sited in areas where the air quality does not meet federal requirements. Such non-attainment areas usually require offsets; that is, the removal of a more polluting device before the new lower polluting system can be installed. This approach slowly reduces the area pollution levels while maintaining adequate power supplies. The TCPS will not require offsets and will be readily permitted for power generation in areas where gas turbines are unacceptable even with the lowest NOx emission combustion system that is practicable. Thus the initial market targeted for the TCPS is one that is not available to gas turbines alone. This market expansion will be spearheaded by a 880-kW TCPS (based on a 300-kW gas turbine) that fits well with the emerging dispersed power market.

DEVELOPMENT NEEDS

System Integration

The development of a TCPS will require solving a number of integration problems faced by both the gas turbine and the fuel cell. Starting, and control of the combined system will be the main developmental areas needing innovation. Starting will include the development of a new combustion system capable of operating with wall temperatures close to 1800 F. A cast, low-sulfur, single-crystal superalloy could be used as could ceramic composites. Initially superalloy materials will probably be used with ceramic materials entering service in later models. The fuel system for the start combustor, at least that part that which will be exposed to the fuel cell exhaust, will also have to be thermally tolerant. This will force the use of new and novel fuel injectors or injectors made of unusual materials.

System Controls

The control of the TCPS will be completely different from that used on the simple cycle gas turbines of today. This control system will probably be based on electrical output (frequency and power) and will have to be developed and integrated with the fuel cell power conversion equipment. The gas turbine part of the system will probably use direct drive alternator technologies that with rectification will produce direct current (DC) power. All of the power produced during steady state operation will be added (electrically) to that produced by the fuel cell. During fuel cell warm-up the power produced will be used to power the controls. The controls needed to accomplish these different requirements do not exist and will have to be developed. The alternator will also be used as a “starter” to spin the engine however once light-off takes place the alternator will be switched back to the generator mode. Again the controls required to perform this operation will have to be developed.

CONCLUSION

Preliminary studies of the TCPS have shown that its performance is much better than expected, especially the efficiency. The efficiency is some three to five points higher than originally anticipated. Costs are acceptable for the introductory models. And, with full production, cost reductions will make the system competitive with all future energy conversion systems of the same power output. Despite the identified problems that must be overcome in creating a viable control system it is believed that they are not insurmountable and can be solved with extensions of existing systems.

In general it can be said that TCPS will provide, with ease, higher efficiencies than either the gas turbine or fuel cell alone. In addition if a gas turbine or fuel cell where to be “pushed” to provide efficiencies in excess of 60% which is typical of TCPS the associated manufacturing costs would be considerably higher.

Overview

- Basis for Interest
- Preferred-Cycle Technology
- Cost Effectiveness
- Development Needs
- Market Niche
- Product Timing
- Product Cost Projections

Tandem Cycle Power Systems (TCPS)

Integrated Fuel Cell - Gas Turbine

- **Synergy**
  - **Efficiency of TCPS Higher Than Either Fuel Cell or Gas Turbine Alone**
  - **Costs for a Given Efficiency Are Lower Than Either Fuel Cell or Gas Turbine System Alone**

Cycle Selection

- Topping is Favored
  - Higher Oxygen Concentration at Cathode
  - Fewer Stacks
  - Higher Power Density

- Bottoming is Under Consideration
  - Easier Starting
  - Simple Control System

- Indirect Fired System
  - Needs More Study
  - Requires Material Development (Heat Exchanger)

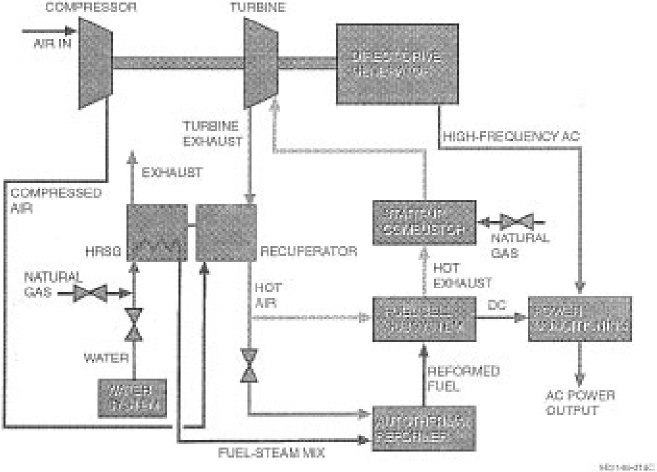
TCPS Integration

- **General Requirements: For Maximum Efficiency**
  - **Convert Most of the Energy with Fuel Cell**
  - **Use Fuel Cell in "Topping Mode"**

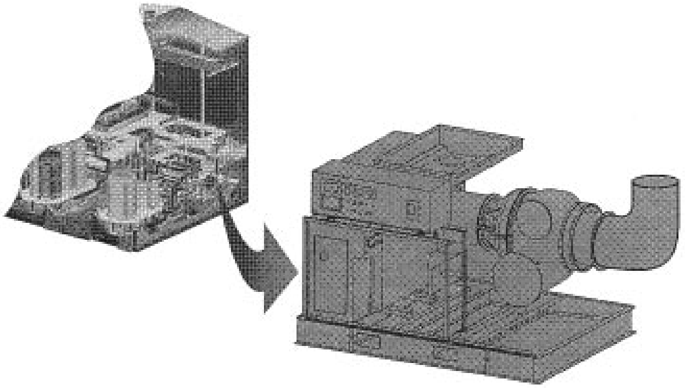
- **Gas Turbine Characteristics**
  - **Low Specific Power**
  - **Low Firing Temperature**
  - **High "Combustor" Inlet Temperature**
  - **High "Combustor" Inlet Pressure**

- **Fuel Cell Characteristics**
  - **Part of Fuel Burned to Heat Fuel Cell**
  - **Efficiency Increases with Pressure**
  - **Efficiency Increases as Power Decreases**

Integrated Gas Turbine and Fuel Cell

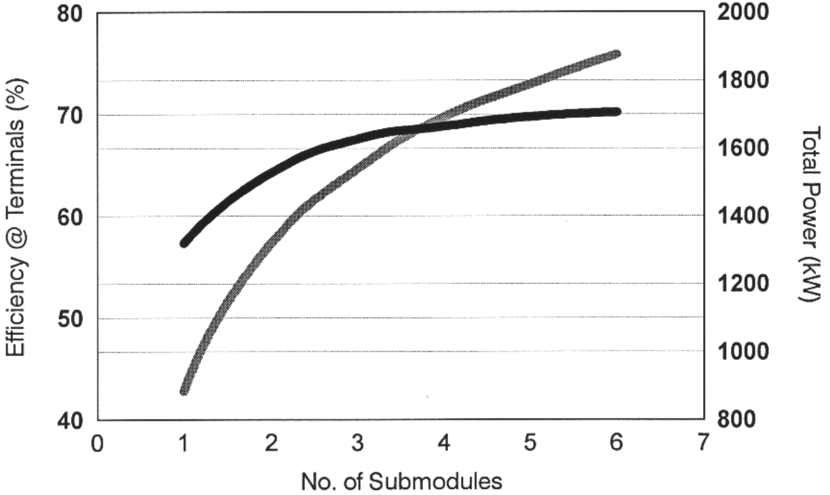


Fuel Cell Balance of Plant (BOP)



Tandem Cycle Power System (TCPS)

DDTG Based System - Performance



DDTG can be integrated with 1 to 6 submodules

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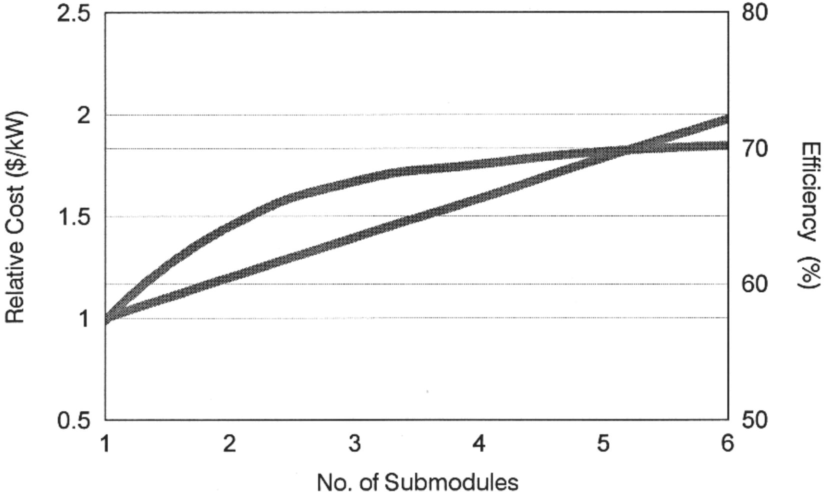
Tandem Cycle Power System

DDTG Based System - Costs



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Gas Turbine Fuel Cell Integration - Solid Oxide Fuel Cells

Efficiency

• No Carnot Cycle Limitations	
• Combined-Cycle Bottoming	75-80%
• Large, High Pressure Systems	65-70%
• Small, Low Pressure Systems	58-63%

System Cost Trade-Off

Life Cycle

- Increasing Stack Count
  - Increases First-Cost, Efficiency

- Increasing Efficiency
  - Decreases Life-Cycle Cost

- Overall Cost-Effectiveness
  - Subsystem Efficiencies
  - Fuel Prices
  - Load Profiles
  - Capital Charges

TCPS Markets

- Entry Market
  - Non-Attainment Areas in US
  - Metropolitan Areas in Europe & Japan

- Main Market
  - Island Nations
  - Large Developing Countries

Technical Development Needs

Gas Turbine

- Develop Uncooled, Start-Up Combustor
- Create Start-Up Combustor Fuel System
- Produce Control System (Based on Power Output)
- Integrate Fuel Cell Subsystems

Summary

- Target Size: 1-to-2 MW
- Introduction in 2004
- Target Cost < $650 kW
- Large Systems < $600 kW
- Dispersed Power Generation in Nonattainment Areas
- Fuel Cell Topping Cycle